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Research Article

Secondary Bud Gas Exchange, Growth, and Fruitfulness of *Vitis vinifera* L. cultivars, 'Grenache' and 'Cabernet Sauvignon' Grown on the Texas High Plains

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Abstract

In 2017, the grape and wine industry had an overall economic impact of $13.1 billion within the state of Texas. The majority of grapes grown in Texas are produced within the Texas High Plains American Viticultural Area (AVA). However, vineyards within the Texas High Plains AVA are subject to late spring frosts which can potentially diminish fruit quality, and reduce crop production. To assist in planning and production efforts, Texas High Plains AVA grape growers require information regarding vine secondary bud growth and fruitfulness. Therefore, the objectives of this experiment were to compare the growth and fruitfulness of shoots grown from primary and secondary buds of *Vitis vinifera* L. 'Grenache' and 'Cabernet Sauvignon' vines grafted to 110R rootstocks. Vines were planted in an experimental vineyard in 2008. Each year over two consecutive growing seasons (2016 – 2017) vines were exposed to the following treatments: primary bud growth intact, and following bud break allowing primary bud shoot growth to reach 15.0 cm in length then removing primary bud shoots (forcing growth from secondary buds). Gas exchange, growth, fruitfulness, and fruit total soluble solid data were collected each year. Collected

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data followed similar trends each growing season. Hence, data from each growing season were pooled. Gas exchange data indicate leaves from primary shoots had lower photosynthetic rates, and stomatal conductance when compared to leaves grown on secondary shoots. In addition, 'Grenache' leaves had greater gas exchange when compared to 'Cabernet Sauvignon' leaves. Pruning weights, vine yield, cluster mass, and total soluble solids were greater for shoots grown from primary buds. 'Cabernet Sauvignon' vines had greater pruning weights, but 'Grenache' vines had greater crop load (Ravaz Index) and cluster mass. Yield and total soluble solids did not differ between grape cultivars, but the number of clusters from each vine, and berry mass varied with cultivar and bud treatment. In the late spring frost-prone Texas High Plains AVA, cultivar selection continues to be a critical factor for vineyard success. Results indicate decreased yields from all vines with shoot growth only from secondary buds. However, even though 'Grenache' and 'Cabernet Sauvignon' vines responded differently to bud treatments ('Cabernet Sauvignon' vines generally produced a greater number of smaller clusters when compared to 'Grenache' vines), for each cultivar overall yield was similar across all bud treatments. Therefore, Texas High Plains AVA and other grape producers now have additional information that may assist them when making critical vineyard management choices.

Keywords

Compound bud, primary bud, spring frost injury, gas exchange

Introduction

Although grapes have been grown in Texas since the mid-1600's, the modern commercial viticulture industry is relatively young (Townsend et al. 2016). However, within the United States Texas ranks fifth among all states in wine production (behind California, Oregon, New York, and Washington) (Townsend et al. 2016). In 2019 within the state of Texas there are more than 2,023 ha of fruit bearing vineyards (approximately 324 non-bearing ha), and greater than 500 wineries (Texas Wine and Grape Growers Association 2020, United States Department of Agriculture 2019). Currently, the Texas wine and grape industry employs more than 100,000 people, and contributes more than $13.1 billion annually to the state's economy (John Dunham and Associates 2017, United States Department of Agriculture 2019). Although over 50 grape cultivars are grown within Texas, the top five grape cultivars grown within the state are: *V. vinifera* 'Cabernet Sauvignon' (251 ha), *V. vinifera* 'Tempranillo' (166 ha), *V. vinifera* 'Merlot' (125 ha), *V. vinifera* 'Mourvedre' (101 ha), and *V.* spp. 'Blanc du Bois' (93 ha) (United States Department of Agriculture 2019). Although a number vineyards within Texas are located outside an American Viticulture Area (AVA) (Townsend and Hellman 2014), there are currently eight AVAs within the state of Texas (Takow et al. 2013, Townsend and Hellman 2014). Despite extraordinary recent growth (Townsend and Hellman 2014, Townsend et al. 2016), viticulturists in Texas face a number of significant biological and geophysical challenges to produce quality grapes (Kamas 2017, Townsend and Hellman 2014).

The vast majority of grape bearing ha in Texas (60%), and grape production (73%) are located in the Texas High Plains AVA (United States Department of Agriculture 2019). The Texas High Plains AVA is composed of approximately 3,596,900 ha in western Texas (Fig. 1), and the elevation ranges from 914 to 1,250 m above mean sea level (Hellman et al. 2011). Climate in the Texas High Plains AVA is semi-arid with mild winters and hot summers (Hellman et al. 2011). Within the AVA, mean annual precipitation ranges from 41.4 to 53.6 cm (Hellman et al. 2011). In addition, mean growing degree days (10 °C, 1 Apr. – 31 Oct.) range from 2,028 in the north to 2,635 in the southern regions of the AVA (Hellman et al. 2011). Due to favorable soil conditions (deep, well-drained alluvium) (Hellman et al. 2011, Kamas 2017), coupled with favorable climate (low night air temperatures due to high elevation, low humidity, abundant light, and low precipitation), and low biotic pressure (low insect pest infestation and fungal diseases), since its inception in 1993 the Texas High Plains AVA has gained the reputation of producing satisfactory yields, and high quality fruit (Hellman et al. 2011). Because of these advantages, grape growers have experimented with growing numerous cultivars within the Texas High Plains AVA (Hellman et al. 2011). In fact, 2019 harvest information was collected for over 36 grape cultivars grown in the Texas High Plains AVA (United States Department of Agriculture 2019). However, Hellman et al. 2011 and Kamas 2017 suggest the Texas High Plains AVA may be best suited for warm and hot climate grape cultivars. Data from 2019 indicate the top five grape cultivars (based upon vineyard land area) grown within the Texas High Plains AVA were two Bordeaux cultivars (‘Cabernet Sauvignon’ (174 ha) and ‘Merlot’ (89 ha)), one Spanish cultivar (‘Tempranillo’ (77 ha)), one Rhone cultivar (‘Mourvedre’ (73 ha)), and one Italian cultivar (‘Sangiovese’ (69 ha)) (United States Department of Agriculture 2019).

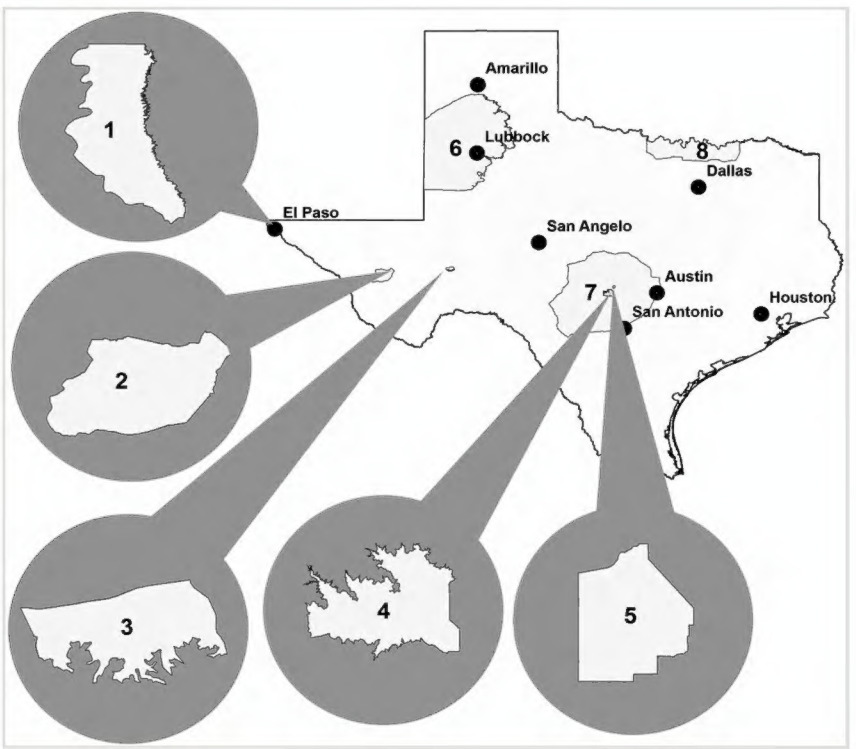

Figure 1. doi

Location of the eight American Viticultural Areas in Texas: 1) Mesilla Valley, 2) Texas Davis Mountains, 3) Escondido Valley, 4) Fredericksburg in the Texas Hill Country, 5) Bell Mountain, 6) Texas High Plains, 7) Texas Hill Country, and 8) Texoma (Takow et al. 2013).

Despite Texas High Plains AVA vineyards producing the majority of wine grapes within the state (Hellman et al. 2011, United States Department of Agriculture 2019), climate conditions within the Texas High Plains AVA (high wind speeds, thunderstorms, hail, extreme diurnal winter and spring air temperatures) (West Texas Mesonet 2020) can be challenging for growing grapes (Basinger and Durham 2000, Johnson and Hilsenbeck 1989, Lipe and Perry 1988, Townsend and Hellman 2014). Late spring frosts are a common concern for vineyard managers in Texas, and across the world (Centinari et al. 2016, Davenport et al. 2008, Evans et al. 2019, Friend et al. 2011, Frioni et al. 2017, Stafne and Puckett 2011). A recent survey involved over 112 Texas grape growers, and indicated the most common cause of crop loss throughout the state was late spring frost damage. Whereas geophysical hazards such as hail, high wind, drought, severe winter cold air temperatures, and late spring frosts were listed as greatest challenges by growers within Texas High Plains AVA (Townsend and Hellman 2014). In addition, crop loss data from crop insurance agencies during a twenty year (1991 – 2010) period indicated spring frost damage was the most reported cause of crop loss within Texas High Plains AVA vineyards (Townsend and Hellman 2014). To combat this commonly occurring hazard of post budbreak, late spring frosts, producers within the Texas High Plains AVA have resorted to numerous mitigation strategies to reduce crop loss (cultivar and rootstock selection, late or double pruning, cover crops, overhead winter irrigation, site selection, vine training, wind turbines, and vineyard heaters (Kamas 2017, Lipe et al. 1992, Townsend and Hellman 2014). However, despite these precautions late spring frosts reduce yield in many Texas High Plains AVA vineyards (Lipe et al. 1992, Townsend and Hellman 2014).

Incidence and severity of damage due to late spring frost depends on plant susceptibility factors, minimum air temperature achieved, and length of time at or below the critical temperature which can damage new growth (Friend et al. 2011). An air temperature of -2.0 ºC is widely considered as critical to cause injury to non-dormant grapevines (Barlow 2010, Evans et al. 2019, Fuller and Telli 1999, Fuller 2002). However, vine tissue temperature can vary depending on air temperature (Evans et al. 2019, Leuning and Cremer 1988), and additional variables (grapevine cultivar, soil and surface moisture levels, presence of a cover crop, soil cultivation, soil temperature, presence and quantity of ice nucleating bacteria, and stage of vine phenological development) which may affect critical vine frost injury temperature (Evans et al. 2019, Fuller and Telli 1999, Gardea 1987, Johnson and Howell 1981a, Johnson and Howell 1981b, Luisetti et al. 1991, Snyder 2001, Sun et al. 2017, Trought et al. 1999). Friend et al. (2011) reports replacement of shoots killed in a late spring frost event result in depletion of vine carbohydrate reserves, which negatively affects future yield and vine productivity. Therefore, results of late spring frost damage are often reduction in yield during the current growing season, and possibly yield reduction in the subsequent growing season (Stafne and Puckett 2011, Trought et al. 1999).

During the growing season, *Vitis* species develop a compound bud composed of primary, secondary, and tertiary buds in each leaf axil (node) (Kamas 2017), and each bud represents a compressed shoot capable of growth (Washington State University Extension 2011). Over winter, compound buds are covered and protected from frost by a bud scale,

and remain dormant (Barlow 2010). However, Andrews et al. 1984 found primary buds to be the least hardy of the three compound buds (followed by secondary, and tertiary buds). Andrews et al. 1984 and Barlow 2010 indicate the amount of supercooling (temperature of water in buds dropping below freezing point without becoming ice) a bud tolerates was inversely proportional to the volume of water contained within each bud. Primary buds being the largest, therefore contain the greatest volume of water, and exhibit the least hardiness, while tertiary buds (smallest of the three compound buds) are reported to be the most hardy among the three (Andrews et al. 1984). Despite not being cold hardy, primary buds are the most fruitful of the three compound buds (Andrews et al. 1984). Therefore, vines damaged by late spring frosts, produce shoots mainly from secondary buds, and tend to have lower fruit yield compared to vines undamaged by spring frosts (Barlow 2010, Dry 2000, Jones et al. 2010, Khanduja and Balasubrahmanyam 1972, Sanchez and Dokoozlian 2005). Furthermore, sunlight plays a critical role in development of primary bud inflorescence primordia by increasing bud diameter with increasing sunlight exposure (Sanchez and Dokoozlian 2005). However, sunlight does not appear to have an influence on inflorescence primordia of secondary buds (Dry 2000, Sanchez and Dokoozlian 2005). Therefore, when compared to inflorescence primordia of primary buds, inflorescence primordia of secondary buds are smaller, and in part explains why shoots from secondary buds often produce smaller fruit clusters (Dry 2000, Sanchez and Dokoozlian 2005). In addition, compared to shoots from primary buds, shoots from secondary buds tend to have lower pruning weights, and may have similar bunch mass, berries per cluster, berry weight, and fruit quality (Barlow 2010, Evans et al. 2019, Friend et al. 2011, Jones et al. 2010, Stafne and Puckett 2011).

Because frost damaged primary shoots are generally replaced by shoots produced from quiescent, secondary buds (Friend et al. 2011), Texas High Plains AVA grape growers desire to know the disparity of grapevine fruitfulness, and fruit quality between primary and secondary bud shoot growth. However, because late spring frost events are challenging to predict, the extent of fruitfulness and fruit quality differences between shoots grown from primary, and shoots grown from secondary buds have not been adequately described for *V. vinifera* cultivars grown within the Texas High Plains AVA. Therefore, the aim of this study was to compare impact of a simulated late spring frost event on leaf gas exchange, growth, yield, and fruit quality of field grown vines within the Texas High Plains AVA.

Methods and materials

Experiments were conducted during the 2016 and 2017 growing seasons at the Texas A&M AgriLife Research and Extension Center, Lubbock, TX (33°41’33"N, 101°49’17"W) research vineyard. The research vineyard is located within the Texas High Plains AVA and within the U.S. Department of Agriculture's hardiness zone 7b (United States Department of Agriculture 2012). Soil characteristics for the vineyard site are a deep, well-drained Olton series fine sandy loam, and have been described previously (Lipe and Perry 1988). Experimental vines were established *V. vinifera* ‘Grenache’ FPS 04 and ‘Cabernet Sauvignon’ FPS 07 vines, bench grafted to 110R rootstocks. Vines were planted in 2008 at

a 1.8 × 3.0 m vine by row spacing, with a north-south row orientation. Soil under vines was kept bare by tilling, and herbicide treatments. Vines were bilateral cordon trained (cordons established 0.9 m above the soil), and spur-pruned to four spurs for each cordon, with two buds for each spur. Canopies were managed in a sprawl configuration, with single foliage catch wires at ≈ 15.0 cm, and ≈ 37.0 cm above each cordon (Plank et al. 2019).

To simulate late spring frost damage to new shoots (secondary shoot treatment (SST)), primary shoot growth was allowed to grow following primary bud break until new shoots reached approximately 15.0 cm in length. For two consecutive growing seasons, the initial 15.0 cm of growth from primary buds was removed by pruning (shoot removal pruning was completed 9 May in 2016, and 25 Apr. in 2017), and secondary buds were induced to break (Schrader et al. 2019). Following bud break, shoots for control plants (primary shoot treatment, (PST)) were not removed. Each year, dormant prunning was conducted 1-2 weeks prior to budbreak. Vines were organized in a randomized complete block design with six blocks within two vineyard rows. Within each block, there were four adjacent vines of each cultivar. Within the four adjacent vines of the same cultivar, shoot treatments (PST or SST) were randomly implemented on two vines. Therefore, there were 36 total vines, and 18 vines for each cultivar and shoot treatment combination. Prior to, and during experiment years, vines were irrigated through a drip irrigation system (Plank et al. 2019). In addition, during each growing season, all vines were managed according to viticultural practices common for the Texas High Plains AVA (Kamas 2017, Townsend and Hellman 2014).

During three cloudless days in 2016 (6 May, 13 Jun., 25 Jul.), and 2017 (6 Jun., 20 Jul., and 7 Aug.), mid-day (solar noon ± 1 hr.) leaf stomatal conductance (g_s), and net photosynthetic rate (P_N) were measured using two LI-6400 XT machines (Li-Cor Biosciences Inc., Lincoln, NE). Gas-exchange data collected 6 May 2016 was taken prior to instigating SST. Intrinsic water use efficiency (WUE_I) was calculated as the ratio of P_N and g_s (Padgett-Johnson et al. 2003). Each machine was equipped with a 6400-02B red / blue external LED light source, and a CO_2 mixer. To simulate environmental growing conditions, during each daily measurement period light intensity within each LI-6400 XT leaf cuvette was maintained at ambient levels, and chamber CO_2 was sustained at 400 ppm. In addition, prior to and several times during daily measurement periods, each cuvette was clamped to a nearby non-sample leaf and leaf temperature, and ambient vapor pressure deficit were estimated. Conditions within each chamber were then set to closely represent these conditions (Soar et al. 2009). Using each LI-6400 XT machine, gas-exchange data were measured on two arbitrarily selected leaves from a randomly selected block × cultivar × treatment combination. Leaves selected for gas-exchange measurements were the youngest fully opened leaves (7^{th} to 9^{th} node from the tip of the shoot), exposed to full sunlight (Padgett-Johnson et al. 2003). Measurements then continued on random vines within the selected block. Once measurements were completed on all vines within the first block, another block was randomly selected, and measurements were completed as described until gas-exchange had been measured on each vine in the experiment.

Fruit harvest maturity was determined by berry juice assays of total soluble solids (°Brix). To estimate Brix value, 50 berries from each vine were sampled from shoulders, middle, and tip of random clusters (Moyer et al. 2018). Berries were sealed in zipper-locked, air-tight plastic bags, placed in a cooler with ice, and brought to an onsite lab. Berries were crushed using a benchtop juicer. To separate precipitating tissues from supernatant juice for analysis, extracted juice was poured into test tubes, and tubes were centrifuged (OM428 Clinical Centrifuge, IEC International, Needham, MA) for 3 minutes at 2,222 rpm (858 g). Supernatant juice was analyzed for total soluble solids (TSS) using a temperature compensating refractometer (3150 Smart Refractometer; ATAGO, Bellevue, WA). Berries were considered to be at harvest maturity when TSS of PST berries were 22% to 24% (Boulton et al. 1999, Moyer et al. 2018). Following harvest, individual berry weight (same 50 berries from each vine used to measure TSS), the number of clusters harvested from each vine, cluster weight, and individual vine yield were determined. During the spring of 2017 (7 Apr.) and 2018 (3 Apr.), dormant pruning weights were measured for each vine (Moyer et al. 2018). Ravaz Index was calculated as the ratio of berry yield to pruning weight for each individual vine.

Yearly (2016 and 2017) precipitation totals (cm), growing season daily minimum and maximum air temperature (ºC), and mean maximum and mean minimum air temperature (ºC) were also recorded using an onsite weather station (Campbell Scientific, Logan, UT) (Table 1).

Table 1.

Annual cumulative growing degree days (GDD), precipitation, minimum temperature, mean minimum temperature, and mean maximum temperature during the 2016 and 2017 growing seasons. In addition secondary shoot pruning date and harvest date for *Vitis vinifera* 'Grenache' and 'Cabernet sauvignon' vines grafted to 110R rootstocks growing on the same location are shown.

Year	Cumulative GDD[z]	Precipitation (cm)	Temperature (ºC)[y]				Date	
			Minimum	Maximum	Mean minimum	Mean maximum	SST[x] pruning	Harvest
2016	2,779	29.9	0.1	42.8	15.6	30.3	9 May	28 Aug.
2017	2,644	46.7	-2.2	44.4	14.9	29.7	25 Apr.	14 Sept.

[z]Growing degree days (10.0 ºC); [y]Climate date from 1 Apr. to 31 Oct; [x]Secondary shoot treatment.

Growing degree day (GDD) heat unit accumulation was calculated from 1 Apr. to 31 Oct. for each experiment year using the equation (Moyer et al. 2018):

$$GDD = \sum (Tmax + Tmin)/2 - Tbase$$

Where, T_{max} and T_{min} are mean daily maximum and minimum temperatures (ºC) respectively, and T_{base} is the base temperature for grapes (10 °C) (Moyer et al. 2018). If the GDD calculation resulted in a negative number, the calculated negative number was reset to zero (Moyer et al. 2018). As discussed previously, -2.0 ºC is considered the critical

air temperature for the injury of non-dormant grapevines (Barlow 2010, Evans et al. 2019). Therefore, to view past history of late spring frosts for the two highest grape-producing areas within the Texas High Plains AVA (Lubbock and Terry counties), 20 year (2000 – 2019) minimum recorded air temperature between 1 Mar. and 30 Apr. (depending upon cultivar budbreak within the Texas High Plains AVA generally occurs mid to late March) were collected from two rural weather stations (one in Lubbock County, and one in Terry County) (National Oceanic and Atmospheric Administration 2020). For this 20 year time period, the number of days for each day of the year between 1 Mar. and 30 Apr. when the minimum daily air temperature was at, or below -2.0 °C was noted. The total number of days for each day of the year (1 Mar. – 30 Apr.) air temperature was at or below -2.0 °C (years 2000 – 2019) for Lubbock and Terry Counties were plotted against the day of the year. Also, for each county accumulative days, air temperature was at or below -2.0 °C for the same time period were plotted against the day of the year. In addition, mean daily low air temperature (1 Mar. – 30 Apr.) over the 20 year time period (2000 – 2019) was graphed against the day of the year.

Daily gas-exchange, pruning, yield, and fruit data means were exposed to analysis of variance using the General Linear Models procedure appropriate for a randomized complete block design (SAS version 9.4, SAS Institute, Cary, NC). For each growing season, gas-exchange daily means indicated similar trends (no interaction found for data from separate years). Therefore, daily gas-exchange data from within each growing season were pooled. However, gas exchange data from 6 May, 2016 (prior to instigating SST) was not pooled with other gas exchange dates. In addition, pruning weight, yield, and fruit data means followed similar trends for each growing season (no interaction found for data from separate years). Therefore pruning weight, yield, and fruit data means from 2016 and 2017 were also pooled for statistical analysis. If mean differences were detected, least square means were separated by Tukey-Kramer's procedure (a = 0.05). Pooled least square means for gas-exchange parameters (P_N, g_s, and WUE_I) were plotted by bud treatment, and grape cultivar. Figures was created using Sigma Plot software (version 14.0, Systat Software, San Jose, CA).

Results

Historical climate data (2000 – 2019) for Lubbock and Terry counties indicate numerous late spring frosts occurred in each location (Fig. 2). Over the past 20 years in Terry County, air temperature reached -2.0 °C or lower, as late as 25 Apr. Similarly, the latest damaging frost date over the past 20 years in Lubbock County appears to be 24 Apr. Both Terry and Lubbock Counties follow similar trends for the number of frost dates in Mar. and Apr. In Lubbock County, 89% of potential damaging frost days occurred before 1 Apr., while in Terry County 84% of potential damaging frosts occurred prior to 1 Apr. (Fig. 2). Although damaging frost trends are similar between counties, total of damaging frost days between 1 Mar. and 30 Apr. in Lubbock and Terry Counties differed. Over the 20 year data collecting period, there were 30 more potential damaging frost days in Terry County (118 days) when compared to Lubbock County (88 days). For 1 Mar., mean daily low temperature in Terry

County was -0.8 °C, and increased to 9.5 °C on 30 Apr. In Lubbock County, 1 Mar. mean daily low air temperature was -0.4 °C and rose to 10.4 °C on 1 Apr. In addition, over the same 20 year period mean, the daily low air temperature was slightly greater in Lubbock county (5.9 °C), compared to Terry county (4.8 °C) (Fig. 2).

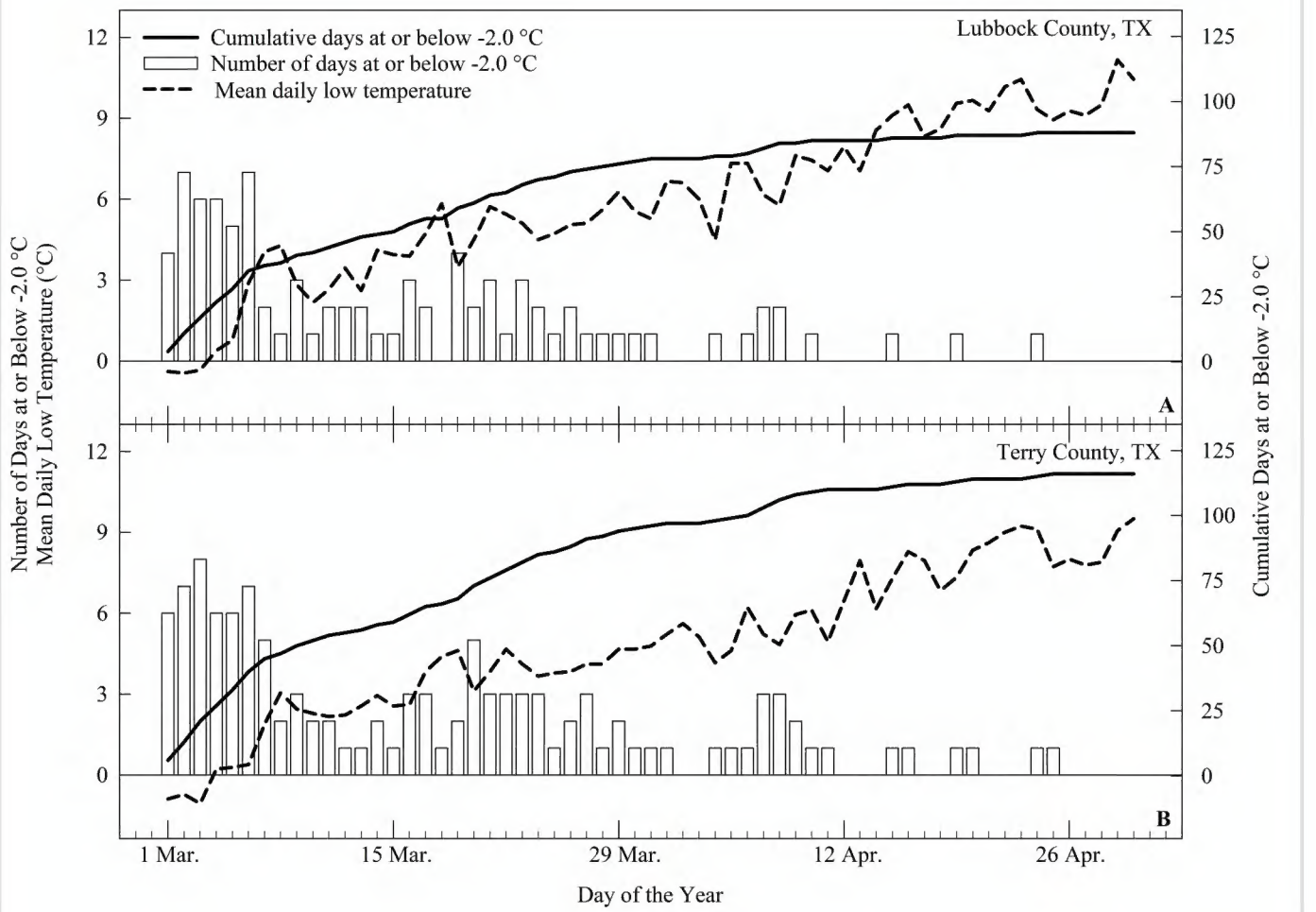

Figure 2. doi

Total number of days (1 March - 30 April, 2000 - 2019) air temperature was at, or below -2.0 °C for two rural locations within the Texas High Plains AVA (Lubbock County, TX (A), and Terry County, TX (B)). In addition, mean, daily low temperature, and cumulative days at, or below -2.0 °C for each location.

Growing degree days data during each experiment growing season (1 Apr. – 31 Oct.) indicate the 2016 growing season was somewhat warmer (5% greater number of GDD) when compared to the 2017 growing season (Table 1). In fact, minimum, mean minimum, and mean maximum air temperatures in 2016 were greater when compared to air temperatures during 2017. However, the greatest air temperature recorded during the experiment (44.4 °C) was recorded on 17 Jun. 2017. In addition, the 2017 growing season received 36% more precipitation compared to the 2016 growing season (Table 1).

Initial (pre-SST) gas-exchange measurements from 2016 indicate no differences between SST and PST leaf gas-exchange data for P_N, g_s, or WUE_I (data not shown). However, initial data from 2016 show leaf P_N and g_s were greater for 'Cabernet Sauvignon' vines compared to leaf P_N and g_s for 'Grenache' vines. In addition, the initial 2016 mid-day leaf WUE_I was greater for 'Grenache' vines compared to mid-day WUE_I of leaves from

'Cabernet Sauvignon' vines (data not shown). Pre SST mid-day leaf gas exchange data for the 2017 growing season was not available for analysis. Pooled (2016 and 2017) leaf gas exchange data indicated leaf P_N and g_s were greater (8% and 15%, respectively) for SST vines, while WUE_I did not differ between leaves from SST and PST vines (Fig. 3). Cultivar leaf gas-exchange data reveal P_N and g_s were greatest (9%, and 14%, respectively) for 'Grenache' vines (Fig. 3). Similar to SST and PST treatments, WUE_I did not differ between cultivars (Fig. 3).

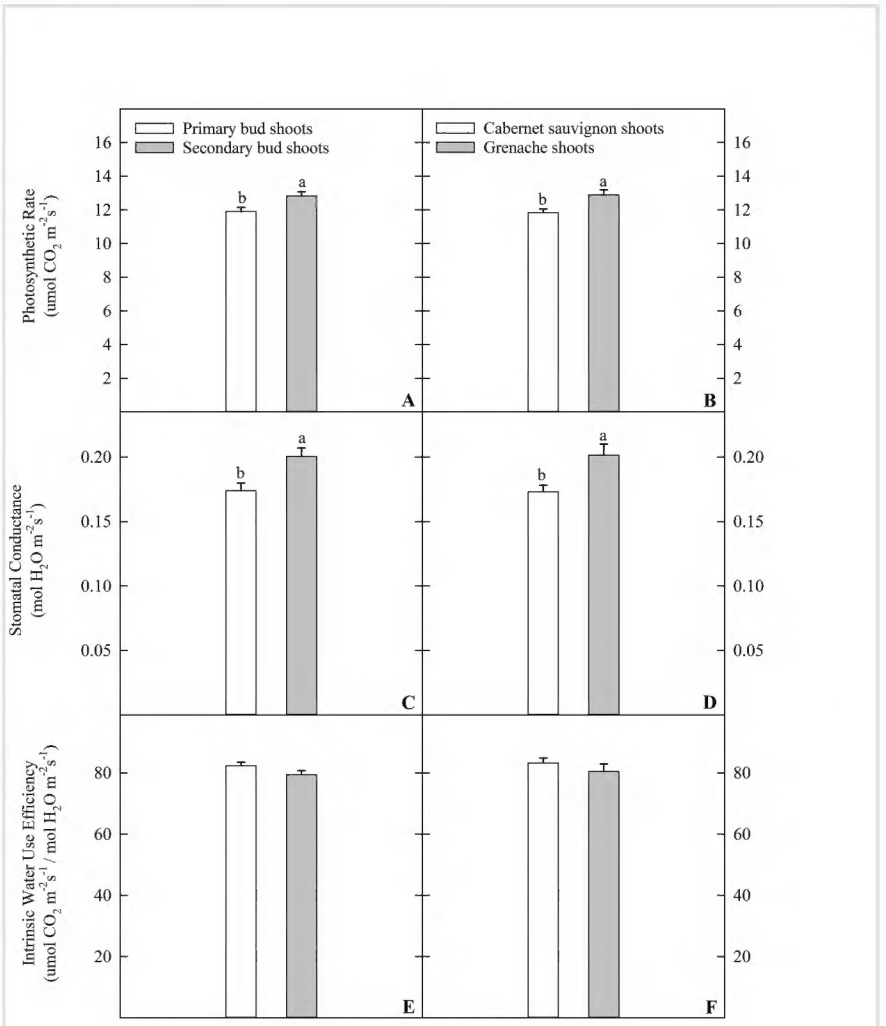

Figure 3. doi

Effects of primary or secondary bud shoot growth, and cultivar on mid-day leaf photosynthetic rate (**A, B**), stomatal conductance (**C, D**), and intrinsic water use efficiency (**E, F**) for field grown *Vitis vinifera* 'Grenache' and 'Cabernet Sauvignon' vines grafted to 110R rootstocks. Each bar represents least square mean of approximately 180 measurements (2016 and 2017 data was pooled). Letters above each bar represent differences between bud type, or cultivar for each date. If a letter is not present, means are not significantly different. (Tukey-Kramer test, $P \leq 0.05$). Error bars represent SE for each bud type or cultivar.

Pruning weight results indicate greater shoot weight for shoots grown from PST buds, and 'Cabernet Sauvignon' vines (Table 2). In addition, yield was 52% greater for PST vines when compared to SST vine yield (Table 2). Ravaz Index data also did not differ between PST and SST vines (Table 2). However, Ravaz Index in 'Grenache' was approximately 62% greater when compared to Ravaz Index for 'Cabernet Sauvignon' vines (Table 2). Bud growth treatment and cultivar had a significant interaction effect for vine berry mass and

the number of clusters produced by each vine (Table 2). Individual berry mass was greatest for 'Grenache' vines grown from PST buds (Table 2). In fact, the berry mass of PST 'Grenache' vines was 41% greater when compared to 'Cabernet Sauvignon' PST vines, and 64%, and 33% greater when compared to 'Cabernet Sauvignon' SST, and 'Grenache' PST vines, respectively (Table 2). The number of clusters produced by each vine was greatest for 'Cabernet Sauvignon' PST vines, while the number of clusters from each vine were least for 'Grenache' SST vines (Table 2). Cluster mass for PST vines was over 26% greater when compared to cluster mass of SST vines, and mass of 'Grenache' clusters was 52% greater when compared to fruit cluster mass of 'Cabernet Sauvignon' vines (Table 2). A similar treatment trend was found comparing fruit TSS. Vines exposed to the SST treatment had lower TSS (11%) when compared to TSS of PST vines (Table 2). While TSS of 'Cabernet Sauvignon' vines was less when compared to TSS of 'Grenache' vines (Table 2).

Table 2.

Effect of primary or secondary bud shoot growth on pruning weight, yield, and fruit quality characteristics for *Vitis vinifera* 'Cabernet sauvignon' and 'Grenache' vines grown on 110R rootstock at the Texas AgriLife vineyard in Lubbock, TX. Data was pooled from 2016 and 2017 growing seasons.

	Pruning weight (g)	**Yield (g vine^{-1})**	**Ravaz index**	**Cluster mass (g)**	**Cluster vine^{-1}**	**Berry mass (g)**	**TSS^{z} (°Brix)**
Treatment							
Primary buds	344.1 a^{y}	597.5 a	3.28	27.8 a	-	-	24.1 a
Secondary buds	226.2 b	287.6 b	2.18	20.6 b	-	-	21.6 b
Cultivar							
Cabernet sauvignon	357.3 a	445.6	1.53 b	15.9 b	-	-	21.6
Grenache	164.2 b	439.4	3.93 a	32.5 a	-	-	23.9
Treatment × Cultivar							
Cabernet sauvignon × primary	-	-	-	-	33.5 a	0.64 c	-
Grenache × primary	-	-	-	-	15.5 c	1.08 a	-
Cabernet sauvignon × secondary	-	-	-	-	20.1 b	0.39 d	-
Grenache × secondary	-	-	-	-	10.3 d	0.73 b	-
Significance	*P* > F						
Treatment	0.0011	0.0072	0.0518	0.0001	0.0001	0.0001	0.0307
Cultivar	0.0001	0.9552	0.0001	0.0001	0.0001	0.0001	0.0543
Treatment × Cultivar	0.1476	0.6010	0.2124	0.0021	0.0438	0.0241	0.3291

[z]Total soluble solids; [y]Least square means within columns followed by different letter are different by Tukey-Kramer test (P ≤ 0.05).

Discussion

Each experiment year between 1 Apr. and 31 Oct. minimum air temperature dropped to near freezing, or below on two occasions (Table 1). During the 2016 growing season, the air temperature on the morning of 2 Apr. dropped to 0.1 °C. In addition, during the morning of 28 Oct. 2017 air temperature was recorded at -2.0 °C. However, the minimum temperature during the first growing season did not induce frost damage to vines, and minimum temperature during the second growing season (2017) occurred post-harvest. Mean, yearly precipitation within Texas High Plains AVA ranges from 41.4 to 63.7 cm (Hellman et al. 2011), while the mean, annual precipitation for the experiment vineyard is 48.5 cm (National Oceanic and Atmospheric Administration 2020). Therefore, precipitation each year of the experiment (Table 1) was less than mean annual precipitation. In addition, the mean cumulative GDD (°C) for the Texas High Plains AVA ranges from 2,028 to 2,653 (Hellman et al. 2011). During the 2016 growing season, GDD accumulation was 2,779, while 2017 GDD accumulation was 2,644 (Table 1). Although weather data during each growing season of the experiment was near normal, weather data indicate variability from one growing season to the next, which is typical for weather within the Texas High Plains AVA, and throughout Texas (Kamas 2017). Over the past 20 years, the total number of days (after Apr. 1) air temperature was at, or below -2.0 °C in Lubbock, County was 10. However, during the same time period Terry County had 20 dates when air temperature dropped to -2.0 °C, or below (Fig. 2). These data indicate late spring frost damage is more likely to occur in Terry County (where most grapes in the High Plains AVA are grown) compared to Lubbock County (where this experiment took place). In addition, although temperatures < -2.0 °C during Apr. in Lubbock and Terry Counties appear to be uncommon, Hellman et al. (2011), Townsend and Hellman (2014), and Kamas (2017) indicate air temperatures below -2.0 °C during post bud-deacclimation may be detrimental to growing grapes within the Texas High Plains AVA. Although recent crop loss data is not available, Townsend and Hellman (2014) report crop loss data during a twenty-year (1999 – 2010) period. For the Texas High Plains AVA, spring frost damage was the most reported cause of crop loss (71 separate crop loss data reports from Lubbock County during this time period were attributed to late spring frosts) (Townsend and Hellman 2014).

Because post-budbreak, late spring frosts are considered common for Texas High Plains AVA vineyards, producers within the Texas High Plains AVA have implemented numerous mitigation strategies to reduce crop loss due to late spring frosts (Kamas 2017, Lipe et al. 1992, Townsend and Hellman 2014). However, the risk of damage from late spring frosts not only depends upon minimum air temperature and vine susceptibility, but also upon the length of time vine structures (buds, shoots, or leaves) are exposed to the critical air temperature (Friend et al. 2011). Johnson and Howell (1981a) indicate the critical temperature is the lowest temperature a shoot may endure for 30 min or less without injury. However, historical data collected for this report only indicate the minimum temperature achieved each date, not the duration of the critical temperature. In addition, it is important to note critical injury temperature is not just air temperature, but the temperature of the vine structure's surface (Barlow 2010). Vine structure (buds, shoots, or leaves) temperature may be several degrees cooler when compared to air temperature (Trought et al. 1999),

especially in semi-arid climates such as within the Texas High Plains AVA (Barlow 2010). Therefore, using a critical air temperature of -2.0 °C for estimating the number of days over the past 20 years grapevines within the Texas High Plains AVA were exposed to potential late spring frost damage is likely an underestimation.

Under non-water stressed growing conditions, several authors directly compared leaf P_N and g_s of 'Grenache' and 'Cabernet Sauvignon' vines. Bota et al. (2016) indicated field-grown 'Grenache' and 'Cabernet Sauvignon' vines had similar P_N, and g_s. Tomas et al. 2012 grew 'Grenache' and 'Cabernet Sauvignon' vines in containers. Each year over three growing seasons leaf P_N, transpiration (E), and g_s were found to be similar between cultivars. Under semi-controlled conditions, Santesteban et al. (2009) report leaf P_N, E, and g_s were greater for 'Cabernet Sauvignon' vines when compared to 'Grenache' vines. Daily and overall leaf P_N and g_s means for Santesteban et al. (2009) study appear to be similar to previous studies (Bota et al. 2016, Tomas et al. 2012). Similar to Santesteban et al. (2009), in our study, it is interesting to note during the first measurement date of the 2016 growing season (6 May), which was prior to initial SST pruning, P_N and g_s means were greater for 'Cabernet Sauvignon' vines (data not shown). However, post SST pruning, leaf P_N and g_s were greater for 'Grenache' vines when compared to 'Cabernet Sauvignon' vines (Fig. 3).

A number of authors report the sensitivity of grape foliage, yield, or fruit quality to late spring frosts and damage to primary buds (Friend et al. 2011, Moyer et al. 2018, Centinari et al. 2016, Frioni et al. 2017, Stafne and Puckett 2011, Evans et al. 2019, Jones et al. 2010). However, previous research does not indicate leaf gas exchange response differences between foliage grown from primary and secondary buds. Because vine damage in response to late spring frosts is common worldwide (Townsend and Hellman 2014, Centinari et al. 2016, Davenport et al. 2008, Evans et al. 2019, Friend et al. 2011, Frioni et al. 2017, Stafne and Puckett 2011), understanding vine gas exchange parameters after a late spring frost may be a critical vineyard management tool. This appears to be the first research distinguishing leaf P_N and g_s differences between primary and secondary shoots. Why SST and PST leaf P_N and g_s differed is confounding, and unclear. Although treatment differences were not found prior to initiation of SST during the 2016 growing season (data not shown), treatment differences in leaf P_N and g_s were displayed each growing season (Fig. 3). Vine leaf gas-exchange response to daily microclimate conditions (air temperature, vapor pressure deficit, wind speed, etc.) can vary with cultivar (Merli et al. 2015a, Merli et al. 2015b), and microclimate variability between measurement dates occurred (Table 1) (National Oceanic and Atmospheric Administration 2020). Grape leaf gas-exchange may also be influenced by vine water status (Chaves et al. 2007, Padgett-Johnson et al. 2003, Pou et al. 2008), leaf age (Kreidemann et al. 1970, Poni and Giachino 2000, Schultz et al. 1996), leaf shoot position (Poni et al. 1994), ratio of leaf area to fruit demand (source to sink ratio) (Petrie et al. 2000, Poni and Giachino 2000), and leaf exposure to sunlight (Chiarawipa et al. 2012). Although vine water status was not directly measured, because experimental SST vines were irrigated with the same volume as PST vines, experimental vines would not have been exposed to water stress. In addition, leaf gas exchange means from this study appear to be similar when compared to leaf gas

exchange data from previous studies of irrigated vines (Bota et al. 2016, Santesteban et al. 2009, Tomas et al. 2012).

Petrie et al. 2000 demonstrate throughout the growing season grapevine leaf P_N (source) increases or decreases as sink (fruit) demand increases or decreases. Therefore, lower TSS levels in SST fruit possibly increased carbohydrate demand (amplified leaf P_N) in SST vines when compared to TSS levels in fruit of PST vines (Petrie et al. 2000). Schultz et al. (1996) and Poni et al. 1994 indicate maximum leaf P_N and g_s occur when grape leaves are 30 to 40 days old. In addition, late in the growing season, a reduction of maximum P_N occurs simultaneously in sun and shade leaves regardless of leaf physiological age (Schultz et al. 1996). Furthermore, depending upon vine phenology greater leaf gas-exchange occurs on basal leaves near clusters (pre-veraison), or apical leaves positioned near shoot tips (post-veraison) (Poni et al. 1994). Because SST vines lost early shoot growth and had to replace removed shoots and leaves, throughout the growing season it is likely foliage used to estimate gas exchange on SST vines was younger when compared to foliage of PST vines. Therefore, it is probable greater leaf P_N and g_s values found in SST treated vines may be attributed to fruit of SST vines having a greater demand for carbohydrates, and SST vines having newer shoots, and therefore younger leaves throughout each growing season when compared to PST vines (Kreidemann et al. 1970, Poni et al. 1994, Schultz et al. 1996, Petrie et al. 2000).

During the initial measurement date of the 2016 growing season (6 May), which was prior to SST pruning, mean WUE_I was lower for 'Cabernet Sauvignon' leaves when compared to 'Grenache' leaves (data not shown). However, post SST pruning WUE_I was not different between cultivars (Fig. 3). This confirms research by Tomas et al. (2012) but differs from Santesteban et al. (2009), and Bota et al. (2016) who found WUE_I of 'Cabernet Sauvignon' leaves were greater when compared to WUE_I from leaves of 'Grenache' vines. In addition, substantial differences in grapevine cultivar WUE_I have been described. Tomas et al. (2014), and Bota et al. (2016) report a compilation of WUE_I for approximately 80 different grapevine cultivars. Their results indicate WUE_I of non-water stressed 'Grenache' and 'Cabernet Sauvignon' vines were slightly greater than most other cultivars examined, and their data compare favorably to our data. Grapevines are cultivated in many different soil types and climates, and under numerous environmental (solar radiation, temperatures, precipitation, soil moisture levels etc.) conditions. Therefore, it is likely genetic WUE_I variability described in this study between 'Cabernet Sauvignon' and 'Grenache', and variability described by other authors (Bota et al. 2016, Tomas et al. 2012, Santesteban et al. 2009) is due to prevailing environmental conditions at each measurement date (Tomas et al. 2014). For example, Tomas et al. (2012) describe WUE_I of 'Cabernet Sauvignon' and 'Grenache' vines under differing soil moisture scenarios. They report under deficit irrigation, WUE_I increased for 'Grenache' and 'Cabernet Sauvignon' vines when compared to non-stressed vines. Others (Chaves et al. 2007, Bota et al. 2016, Santesteban et al. 2009, Merli et al. 2015a) report similar results.

Similar to P_N and g_s data, this appears to be the first study comparing WUE_I between leaves grown from grapevine primary and secondary shoots. However, unlike leaf P_N and g_s means, WUE_I differences between SST and PST vines were not found (Fig. 3). Because

grapevine leaf P_N and g_s are clearly coupled (Chaves et al. 2007), WUE_I allows comparison of leaf-level WUE at comparable evaporative demand (Flexas et al. 2010). Since WUE_I is calculated from the ratio of P_N to g_s, although P_N and g_s were greater in SST leaves the ratio of P_N to g_s did not differ between PST and SST leaves (Fig. 3). In addition, WUE_I for PST and SST vines was comparable to WUE_I for non-water stressed 'Grenache' and 'Cabernet Sauvignon' vines, and reports from previous research (Bota et al. 2016, Tomas et al. 2014). An aditional indication vines were healthy, and not lacking in soil moisture throughout each growing season.

It is a commonly understood pruning weight data from shoots grown from *Vitis* spp. secondary buds are less when compared to pruning weight data of shoots grown from vine primary buds (Creasy and Creasy 2018). However, few studies directly compare pruning weight data from primary and secondary bud shoots. Jones et al. 2010 indicate pruning weights from 20 year old, spur pruned 'Pinot Noir' vines grown from secondary buds had 47% less mass when compared to vines grown from primary buds. In addition, the mean shoot length (a representation of pruning weight) of shoots grown from primary buds of five year old, interspecific hybrid (MN 1094 × Ravat 262 'Marquette') vines were 28% greater when compared to the mean shoot length of shoots grown from secondary buds (Frioni et al. 2017). These results are analogous to our data in which mean pruning weights from shoots grown from PST buds was approximately 34% greater when compared to mean pruning weights of shoots grown from SST buds (Table 1).

In addition to lower pruning weights, mean vine yield was less for shoots from SST buds when compared to yield from shoots of PST buds (Table 1). Once again, there is abundant information in the literature which indicates a decrease in yield would be expected when primary buds are damaged during late spring frosts, and vineyard yield is dependent upon secondary bud fertility (Barlow 2010, Friend et al. 2011, Frioni et al. 2017, Jones et al. 2010, Kamas 2017, Kasimatis and Kissler 1974, Stafne and Puckett 2011). Low fruitfulness of secondary buds is likely related to the lack of dormant inflorescence primordia found in secondary buds of *V. vinifera* cultivars (Sanchez and Dokoozlian 2005). However, in most regions after a late spring frost, the survival of a certain percentage of primary buds is common (Frioni et al. 2017). Barlow (2010) and others (Friend et al. 2011, Frioni et al. 2017) report reduced yields from secondary bud growth may range from 10 to 70% of primary bud yield. Similar reports for yield reductions during years with late spring frosts (and a high percentage of primary buds are eliminated) are reported by Texas High Plains AVA grape growers (T. Montague, personal communication). Therefore, vineyard yield following a late spring frost is generally not entirely dependent upon secondary bud survival. Across PST and SST vines, our data indicate yield differences were not found between 'Cabernet Sauvignon' and 'Grenache' vines (Table 1). Whether shoots from secondary buds exhibit greater, or lesser yield compensation is likely cultivar dependent (Friend et al. 2011). For example, Kasimatis and Kissler (1974) report yield compensation from shoots of primary and secondary buds differed between 'Tokay' and 'Carignane' vines. Additional reports of primary and secondary bud yield differences between cultivars have been published by Sanchez and Dokoozlian (2005), and Dry (2000).

The ratio of yield weight to pruning weight (Ravaz Index) is often used as an expression of crop load to indicate vine balance (Reynolds and Heuvel 2009). For *V. vinifera* cultivars, crop loads in the range of 5 to 10 are often the goal (Bravdo et al. 1984, Bravdo et al. 1985), but crop load is known to differ with cultivar, training system, climate, and soil type (Reynolds and Heuvel 2009, Scheiner et al. 2020). For many grape cultivars, it is thought crop loads above 12 (over-cropping) delay fruit maturation, and reduced wine quality (reduced color, titratable acidity, and proline concentrations) (Bravdo et al. 1984, Bravdo et al. 1985). In the current study, yield and pruning weights of PST shoots were greater when compared to yield and pruning weights of SST shoots. However, the ratio of yield to pruning weight did not differ between PST and SST vines. For numerous grape cultivars, previous work indicates an increase in crop load ratio is mainly related to an increase in vine yield, and a decrease in vine pruning weight (Bravdo et al. 1984, Bravdo et al. 1985, Reynolds and Heuvel 2009, Scheiner et al. 2020). However, for PST vines greater yield was found on vines with greater pruning weights (Table 2). Nonetheless, this was not the case with 'Grenache' vines. Compared across all bud treatments, 'Grenache' vines had lower pruning weights when compared to 'Cabernet Sauvignon' vines, but 'Grenache' and 'Cabernet Sauvignon' yield was similar. When compared to SST vines, PST vines had greater vigor and were more fruitful. These data are an indication of the propensity of primary buds to produce greater shoot growth, and have greater bud fertility when compared to secondary bud characteristics (Dry 2000, Friend et al. 2011, Jones et al. 2010).

Based on crop load data, vines in this study were under cropped (Table 2). When extrapolated by row and vine spacing, the average yield for each vine treatment or cultivar is calculated as 1,072, 517, 800, and 790 kg/ha for PST, SST, 'Cabernet Sauvignon', and 'Grenache' vines, respectively. As discussed previously, greater crop loads tend to impose unfavorable characteristics on fruit and most wine grape cultivars (Reynolds and Heuvel 2009). Research on fruit and wine characteristics from vines with crop loads lower than 5.0 indicate few differences when compared with vines with crop loads between 7.0 and 10.0. Kasimatis (1977) reports when Zinfandel crop loads were reduced to 4.3, there were no differences in wine aroma quality, or taste intensity when compared to wines made from vines with crop loads of 7.5 to 10.0. In addition, Weaver et al. 1961 report 'Carignane' and 'Grenache' vines with crop loads lower than 5.0 did not differ in fruit or wine quality characteristics when compared with vines with crop loads between 5.0 and 10.0 (Bravdo et al. 1984).

For all vines, overall yield was closely related to cluster mass (PST and 'Grenache' vines produced clusters with greater mass), the number of clusters produced from each vine ('Cabernet Sauvignon' PST vines produced the greatest number of clusters, while 'Grenache' SST vines produced the least number of clusters), and berry mass (largest berries were produced by 'Grenache' PST vines, and smallest berries were produced by 'Cabernet Sauvignon' SST vines) (Table 2). It is interesting to note when comparing yield characteristics across cultivars and bud treatments, although 'Cabernet Sauvignon' and 'Grenache' had similar yield, 'Grenache' clusters had greater mass and tended to have a fewer number of clusters from each vine when compared to 'Cabernet Sauvignon' vines. In

addition, 'Grenache' vines produce larger berries when compared to berries from 'Cabernet Sauvignon' vines (Table 2). When compared to shoots grown from primary buds, smaller clusters from shoots grown from secondary buds is well documented, and has been partially attributed to lower TSS, and delay in SST fruit maturity (Dry 2000, Friend et al. 2011). However, others have found clusters, berry mass, and berry weight of fruit grown from secondary buds and primary buds did not differ (Barlow 2010, Evans et al. 2019, Friend et al. 2011, Jones et al. 2010, Stafne and Puckett 2011). Our data indicate crop load and yield (including cluster mass, clusters produced from each vine, and berry mass) response to SST and PST tends to be cultivar specific and relates well to previous research (Evans et al. 2019, Friend et al. 2011, Jones et al. 2010, Sanchez and Dokoozlian 2005, Stafne and Puckett 2011). In addition, it appears SST bud growth had a greater influence on vine yield than SST bud growth had on vine pruning weights. Compared to PST pruning weights, SST bud pruning weights were reduced 34%, while SST yield was reduced 54% when compared to PST yield (Table 2).

Although WUE_I did not differ between SST and PST leaves, or 'Grenache' and 'Cabernet Sauvignon' leaves (Fig. 3), long term plant water use efficiency (defined as the ratio of biomass accumulation or yield, and irrigation volume applied to the vine during the growing season) (Merli et al. 2015b) does appear to differ between cultivars and bud treatments. Although the total irrigation volume applied to each vine is not known, based upon the experimental design and vineyard management practices the same volume of irrigation was applied to each vine regardless of bud treatment, or cultivar. Therefore, indirect comparisons of long term plant water use efficiency (WUE_L) are appropriate. Based upon pruning weight and yield data, over the course of two growing seasons the trend is PST vines had greater WUE_L when compared to SST vines (PST vines had greater yield and pruning weights), and WUE_L for 'Grenache' vines tended to be greater when compared to 'Cabernet Sauvignon' vines ('Grenache' had similar yield with lower pruning weights when compared to 'Cabernet Sauvignon' vines) (Table 2). Although WUE_I is frequently estimated on grapevines to determine vine adaptation to water stress, the correlation between leaf-level water use efficiency (WUE_I) and WUE_L in regard to vine drought tolerance, vine yield, or vine biomass accumulation is not consistent (Merli et al. 2015a, Merli et al. 2015b, Padgett-Johnson et al. 2003, Moutinho-Pereira et al. 2007). In fact, Tomas et al. (2014) concluded WUE_I is not a dependable estimate to predict vine adaptation to a given environment. Canopy structure, night transpiration, and respiration are factors involved in the estimation of WUE_L, but these factors are not considered when calculating WUE_I (Tomas et al. 2012, Tomas et al. 2014).

Fruit quality (TSS) differed for berries from PST and SST shoots, and there was a trend for 'Grenache' berries to have greater TSS when compared to 'Cabernet Sauvignon' berries (Table 2). Kasimatis and Kissler (1974) indicate TSS for berries from primary and secondary buds did not differ for 'Tokay', 'Carignane', 'Zinfandel', 'Chenin Blanc', and 'Grenache' vines. However, titratable acidity was greater for berries from secondary bud growth. Total soluble solids of fruit grown from secondary and primary buds of the interspecific hybrid vine MN 1094 x Ravat 262 'Marquette' differed from veraison until just prior to harvest (approximately 25 days). However, TSS of fruit from primary and

secondary buds was not different when measured at harvest (Frioni et al. 2017). In the same study, results from veraison through harvest indicate pH was lower, and titratable acidity greater for juice from secondary buds when compared to juice from primary buds. In contrast, Jones et al. (2010) found 'Pinot Noir' fruit from secondary buds had lower TSS when compared to fruit from primary buds. Current and previous research indicates the maturation of fruit from secondary buds is likely to be delayed when compared to the maturation of fruit from primary buds (Barlow 2010). Even though in the current study leaves from secondary shoots had greater P_N when compared to leaves from primary shoots (Fig. 3), the need to replace shoots, leaves, inflorescences, and fruit lost from late spring frosts likely redirects carbon partitioning, and further stresses limited vine carbohydrate reserves (Stafne and Puckett 2011, Trought et al. 1999). In addition, the amount of sunlight received by primary buds has been shown to have a significant effect on size inflorescence primordia (Sanchez and Dokoozlian 2005). However, the quantity of sunlight does not appear to have an influence on the size of the inflorescence primordia of secondary buds (Dry 2000, Sanchez and Dokoozlian 2005). Therefore, when compared to berries from primary buds, berries from secondary buds are likely less of a sink for carbohydrates produced from leaf P_N reactions. Furthermore, following a late spring frost many vineyards are likely to have vines with fruit produced from primary and secondary buds. Trought et al. (1999) suggest when primary bud shoots remain viable following a late spring frost event the smaller secondary bud crop load may ripen and mature faster when compared to the larger, undamaged primary crop load. Therefore, following late spring frosts in vineyards with shoots from primary and secondary buds, there is likely to be variability in fruit maturity across the vineyard block, which will result in harvest and management challenges (Barlow 2010, Evans et al. 2019, Jones et al. 2010).

Conclusion

Vineyards within the Texas High Plains AVA are subjected to yield losses and management challenges associated with late spring frosts. In response to selective pruning, gas-exchange, growth, and fruitfulness of shoots produced by secondary buds of 'Grenache' and 'Cabernet Sauvignon' grapevines were compared to shoots grown from primary buds of the same cultivars. This report concurs with previous work which indicates yield, and fruit quality generally suffers when wine grape primary buds are damaged due to late spring frosts. However, it appears this report is the first to conclude that when compared to leaves produced from primary shoots, gas-exchange is greater for leaves produced from secondary shoots. In addition, although, vine vigor, bud fertility and yield data were lower than commonly found within Texas High Plains AVA vineyards, trends for PST, SST, 'Grenache', and 'Cabernet Sauvignon' yield indicate even though 'Grenache' and 'Cabernet Sauvignon' vines had similar yields across PST and SST treatments, PST, SST, and cultivar had an interactive effect on clusters produced from each vine and individual berry mass. Data indicate 'Grenache' (smaller fruit and greater berry mass), and 'Cabernet Sauvignon' (larger fruit and lower berry mass) vines responded differently to PST and SST treatments. To better understand grapevine cultivar interactions with late spring frost damage within vineyards on the Texas High Plains AVA, possible future research may

include post late spring frost vineyard survival and fertility surveys of commonly grown grape cultivars within the Texas High Plains AVA. Vineyard management before and following late spring frosts is critical for current, and future vineyard productivity. Viticulturists within the Texas High Plains AVA now have additional information that may assist them when making these crucial vineyard management decisions.

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Conflicts of interest

Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by Texas Tech University, or Texas AgriLife Research, and does not imply its approval to the exclusion of other products or vendors which may also be suitable.

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